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PRESSURE FLUCTUATIONS ON A FLAT PLATE WITH OBLIQUE JET IMPINGEMENT

by D. R. Strong, T. E. Siddon, and W. T. Chu

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We are indebted to Dr. H. S. Ribner who initiated and supervised this research.

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SUMMARY

A pair of pin-hole microphones were flush-mounted in a heavy metal plate against which a turbulent jet was directed obliquely. Two-point space-time correlations of the fluctuating surface pressure were obtained. The correlation plots define both the local convection speed of the turbulent pressure 'spots' and the scale or average size of the 'spots'. The curvature of the line of maximum correlation indicates a variation of convection speed with position along the plate.

Jet inclinations were used that varied from normal to the plate to glancing incidence. The value of $\sqrt{\overline{p^2}}/q_0$ on the jet centerline was measured as a function of distance X of the plate from the nozzle for the different inclinations, together with some power spectra at fixed X. With normal impingement the value $\sqrt{\overline{p^2}}/q_0$ was very high (compared with boundary layer surface pressures), attaining a maximum value 0.12 at $X/D \simeq 7$. High values are still retained for a range of oblique impingements.

This suggests normal or oblique impingement by jets to simulate the fatiguing of structures by parallel jets or by boundary layers. The impinging jet would provide either accelerated fatigue or (with lower speed jets) increased economy of testing. A jet could moreover simulate boundary layer correlation lengths and convection speeds and avoid the disparity found with siren-generated sound fields used for fatigue tests.

TABLE OF CONTENTS

<u>NOTATION</u>

D	diameter of model jet
p	fluctuating surface pressure
q_o	dynamic pressure ($= \frac{1}{2} \rho_o U_o^2$)
$\mathcal{R}$	correlation coefficient
t, T	time
U_o	exit velocity of jet
U_c	convection velocity
X	downstream distance from nozzle exit
ξ	spatial separation of microphones
θ	complement of angle between plate and jet axis
ϕ	spectral density function
ρ_o	ambient density
τ	time delay
ω	radian frequency
Hz	Hertz, new unit for cycles per second
rms	root mean square

I INTRODUCTION

With the advent of high power engines and high speed aircraft, acoustic fatigue has become a major problem in aircraft operation. Its occurrence in a structure is determined by the acoustic inputs, the dynamic response of the structure, and the fatigue life of the material. Two of the important acoustic inputs are in the form of fluctuating pressures occurring in the 'near field' of a jet engine or rocket exhaust or beneath a turbulent boundary layer.

The following considerations, due largely to H. S. Ribner, have motivated the present work. It is fashionable and relatively economical to use plane or reverberant-field sound waves generated by a siren for fatigue studies. The broad band siren as designed by J. N. Cole, H. E. von Gierke, et al. (Ref. 1) with possible spectral shaping capability as investigated by B. J. Moskal (Ref. 2) may be satisfactory in simulating the acoustic 'far field' input. It will be unsatisfactory in simulating the other two inputs mentioned earlier.

Specifically the siren provides a faulty simulation of the convective decaying pattern usually observed in the pseudoacoustic 'near field' of a jet (see e.g. Refs. 3 and 4) or in the pressure field beneath a turbulent boundary layer (see e.g. Refs. 5 and 6). Firstly, the convection speed is limited to the speed of sound whereas the convection speeds of the pressure patterns in the two cases mentioned are related to the flow speeds. Since the pressure convection speed figures in a resonant response of the panel called 'coincidence' (Refs. 7 and 8), the lack of a proper simulation of the pattern speeds will remain an objection to the siren approach. Secondly, the siren approach will provide unrealistically large correlation areas for the pressure field because they are related to the acoustic wave lengths. Correlations in a jet or boundary layer, on the other hand, correspond to the eddy sizes and are very much smaller. These small correlation lengths are much more effective in exciting higher order panel modes.

The present work was motivated by the idea of using impinging jets to simulate the aforementioned acoustic inputs. It was felt also that in areas where direct jet-induced fatigue is encountered, oblique jets could serve in place of parallel jets, with a saving of power.

The rms pressure level, the power spectral density and the space-time correlation of the pressure field created on a flat plate by the jet impingement were measured. Of these the correlation is particularly important, since it determines the details of the plate vibration response. The survey was done for the most part at a distance of seven diameters downstream at which the fluctuating pressures maximize. Several angles of jet impingement were employed.

II EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 Flat Plate Arrangement

Figure 1 provides a schematic diagram of the flat plate arrangement. A plywood board fitted around a 13 inch square metal plate served to approximate an infinite flat surface. In the plate were a series of holes which could accommodate either steel plugs or flush-mounting pin-hole microphones. The apparatus was mounted on a movable, adjustable frame so that various downstream locations and angular positions were possible.

2.2 Jet Facility

Jet impingement was provided by the UTIAS low speed free jet facility (Ref. 9) which provides a four inch diameter round jet. The boundary layer thickness at the exit is approximately 0.1 inches and the turbulence level within the potential core is less than 1%. All measurements were made with a jet exit velocity U_o of 136 feet per second.

2.3 Measurements of Fluctuating Surface Pressure Level

Measurements of the rms pressure level at points of the plate surface were made with pin-hole microphones in conjunction with General Radio Type 1551-A sound level meters. The microphones were of a capacitive type made by Altec Lansing, and because of the pinhole were characterized by a resonant peak above 2,000 Hz. Equalization filters to suppress this peak (see section "Correlation Technique") were not used in the measurement of overall surface pressure level. The error introduced is considered to be small because the resonant peak lies well above the 'knee' of the pressure spectrum.

2.4 Correlation Technique

Figure 2 illustrates in block-form the system which was used for recording and processing the correlation data. This system is described at length elsewhere (Ref. 10). Basically, it involves the simultaneous recording of signals from two microphones separated by a distance ξ, on the two tracks of a tape-recorder. The tape is played back to analog computer circuits that multiply the two signals and then time-average the product. The result - which is a correlation - is displayed on a digital voltmeter. An adjustable staggered play-back head is used on the tape recorder, which effectively introduces a time delay τ between the two signals as they are fed to the multiplier. The correlation is thus a function of microphone separation ξ and time delay τ. The frequency response of the whole system is $\pm$ 2 db from 20 to 10,000 Hz.

A recent addition to the correlation system is a solid-state automatic control unit designed at UTIAS. Owing to a series of timing and logic circuits coupled to relays it is able to record and process semi-automatically large quantities of data with a considerable saving of time over the old manual methods of operation.

Although the previously mentioned microphone resonance problem did not affect the overall values of surface pressure level, it would influence the correlation data. For this reason, an equalization filter was used with the microphones during the correlation measurements which resulted in a flat frequency response up to 10,000 Hz. The design and characteristics of this filter are outlined in an earlier UTIA report (Ref. 11).

2.5 Spectral Analysis

A Bruel & Kjaer Type 2109 Frequency Spectrometer was used in conjunction with the pin-hole microphone and sound level meter to obtain curves of spectral density for various plate orientations. The equalization filter was not used for these measurements; thus the results were corrected manually for microphone frequency response. The usual correction to 1/3 octave readings for finite band-width was also applied.

III EXPERIMENTAL RESULTS

3.1 Fluctuating Surface Pressure Level

Values of the fluctuating surface pressure level were first obtained as a function of downstream location of the flat plate. In this series of measurements the plate was kept normal to the flow and at each downstream position the surface pressure level was recorded for various cross-stream microphone locations. The data was then converted to the form $\sqrt{\overline{p^2}}/q_o$ and plotted versus X/D as shown in Fig. 3. It is apparent that a maximum pressure of $\sqrt{\overline{p^2}} = 0.12\, q_o$ is obtained for a plate location about seven diameters downstream of the jet exit. We note that this maximum pressure is some 20 times as great as the pressure one expects to find in normal boundary layer flow (e.g. Ref. 12). It was decided to make all further experimental measurements at the location X/D = 7.

The next step was to investigate the effect of various angles of impingement on the pressures measured at X/D = 7. Figure 4 shows the variation of $\sqrt{\overline{p^2}}/q_o$ across the plate for impingement ranging from normal incidence to near-parallel flow. For normal impingement ($\theta = 0^o$) it is noted that the maximum rms pressure is generally constant over the range $0.5 < \xi/D < +0.5$. In order to simulate a uniform fluctuating pressure field typical of boundary layer flow (e.g. Ref. 6), it is obvious that the test panel dimensions must not substantially exceed the jet nozzle diameter at this particular downstream position.

With the incidence approaching a glancing angle ($\theta = 87^o$), the pressure ratio drops to approximately 0.03, or about 5 times that which we would expect in boundary layer flow. For this case the pressure is essentially constant all along the plate; hence, this is more typical of true boundary layer flow.

A cross-plot was made of the data of Fig. 4. The resulting curves (Fig. 5) indicate the variation of $\sqrt{\overline{p^2}}/q_0$ with impingement angle θ.

3.2 Two-Point Space-Time Correlation

The correlation, or time-averaged product of instantaneous pressure measured at two points in the flow, is given in normalized form by

$$\mathcal{R}(\xi, \tau) = \frac{\overline{p(o, t)\, p(\xi, t + \tau)}}{\sqrt{\overline{p(o,t)^2}}\ \sqrt{\overline{p(\xi, t + \tau)^2}}}$$

where

$$\overline{p(o, t)\, p(\xi, t + \tau)} = \frac{1}{T}\int_0^T p(o, t)\, p(\xi, t + \tau)\, dt$$

The correlation coefficient was evaluated as a function of probe separation ξ and time delay τ for various impingement angles at X/D = 7. The electronic correlating system as described in Section 2.4 was used for this purpose. Figures 6 to 9 are plots of the resulting data. The characteristic forms of these correlation curves are in close agreement with those of Refs. 3 and 4. The experimental circumstances differ, however: the results obtained in Ref. 3 are for pressures in the free field of a jet; those obtained in Ref. 4 are for pressures at the surface of a rigid plate lying entirely outside the jet; whereas those found in the present investigation pertain to pressures at the surface of a rigid plate due to direct jet impingement. Qualitatively, they are also similar to those found in turbulent boundary layer flow (Refs. 5 and 6).

If the impingement flow is idealized by assuming that the turbulent eddies move outward from a source which coincides with the point of flow stagnation at the plate, then we would expect a significant degree of correlation between pressures measured at two points on the same radial 'eddy-path'. The physical properties of a particular eddy will gradually change as it moves outward from this origin, hence the correlation coefficient $\mathcal{R}(\xi, \tau)$ decreases steadily with increasing separation and time-delay.

However, the pressures measured at two points on substantially different radial paths will be poorly correlated because different eddies are involved.

A fixed reference point was chosen for one of the microphones, with the second being positioned a radial distance ξ away. For the cases with θ of 30°, 60°, and 87°, the reference point was chosen to correspond with the geometric center-line of the jet, as shown on the inset sketches. For the case of normal impingement, however, it was decided to place the reference microphone at a point on an imaginary projection of the jet nozzle

(i. e. at one radius from the jet center-line). This choice was made to place both microphones on the same "eddy path" after they diverge from the impingement centerpoint, to ensure good correlation.

The rate of decrease of the correlation $\mathcal{R}(\xi, \tau)$ is indicated in Figs. 6 to 9 by an 'envelope' which has been drawn tangent to the family of experimental curves. This envelope actually defines the so-called 'autocorrelation in the moving frame' (Ref. 13), and from it we were able to approximate the eddy convection speed U_c. A curve was plotted of separation ξ versus time delay τ, for points lying on the 'autocorrelation envelope'. The slope $d\xi/d\tau$ of this curve for any particular ξ can be interpreted as the local eddy convection speed U_c at that distance from the reference point. Figure 10 illustrates the resulting variation of U_c with ξ.

Convection speeds ranging from $0.3\ U_o$ to $0.7\ U_o$ are clearly attainable with jet impingement. To properly simulate boundary layer flow, it would be desirable to have a relatively constant eddy convection speed within the physical boundaries of the test panel. It is noted that for the normal impingement case, U_c is approximately constant for separations up to $\xi/D \simeq 0.6$.

By cross-plotting the data of Figs. 6 to 9 it was possible to obtain contours of constant correlation in a plane of separation versus time delay. These curves are presented in Figs. 11 to 14. The dotted line describes the earlier mentioned 'autocorrelation envelope' in the space-time plane, the slope of which approximates the convection speed.

The form of these contours is again very similar to those which have been published elsewhere (Refs. 5 and 10) for the correlation of pseudo-sound pressure beneath an actual boundary layer. The similarity, although only qualitative, seems to indicate that in any particular radial direction the physical process of eddy convection is very much like that encountered in boundary layer flow.

3.3 Spectral Density of Fluctuating Surface Pressure

The spectral density of the surface pressure is shown for various impingement angles and microphone positions in Figs. 15 and 16. The range of nondimensional frequency $2\pi f D/U_o$ corresponds to frequencies f from 40 to 10,000 Hz.

Figure 15 shows two spectra of the fluctuating surface pressure at two positions at normal impingement whereas Fig. 16 shows the spectra for four different impingement angles at the jet axis position. It is interesting to note that even though the flow patterns would be quite different for the cases considered, there is a certain similarity at the high frequency portion of the different spectra except for the extreme case of grazing incidence. The results also show a gradual decrease in magnitude at the low frequency end as the impingement changes from normal to grazing incidence or as one goes away from the jet axis position. This merely reflects the general belief that the formation of large eddies usually depends on the apparatus sizes and/or arrangements.

IV CONCLUDING REMARKS

The measured two-point space-time correlations show resemblance to those for the pseudosound pressure in the 'near field' of a jet or beneath a turbulent boundary layer. They define both the scale and the convection speed of the turbulent pressure spots associated with the eddies. The curvature of the line of maximum correlation indicates a variable convection speed with position along the plate.

The nondimensional rms pressure $\sqrt{\overline{p^2}}/q_0$, measured at the jet stagnation point with normal impingement, is very much higher than the rms pressure under a turbulent boundary layer; a maximum value of 0.12 is recorded at a nozzle-to-plate distance of about 7 diameters. Substantial enhancement is still retained for a range of oblique impingement at the same axial distance.

The spectra of the fluctuating surface pressure on the jet center-line with various inclinations and at two different positions at normal incidence show some kind of similarity at high frequencies. There is a general decrease in magnitude of the low frequency components as the angle of incidence is increased or at positions away from the jet center-line.

It seems quite evident from the present investigation that the impinging jet arrangement may be used for structural fatigue studies to replace either parallel jets or a turbulent boundary layer. However, the radial type flow near the jet center-line at normal impingement may not simulate the proper coincidence effects. One might have to sacrifice the largest enchancement of rms pressure level found for that circumstance and go to more oblique impingement or away from the jet center-line to obtain a more parallel flow condition.

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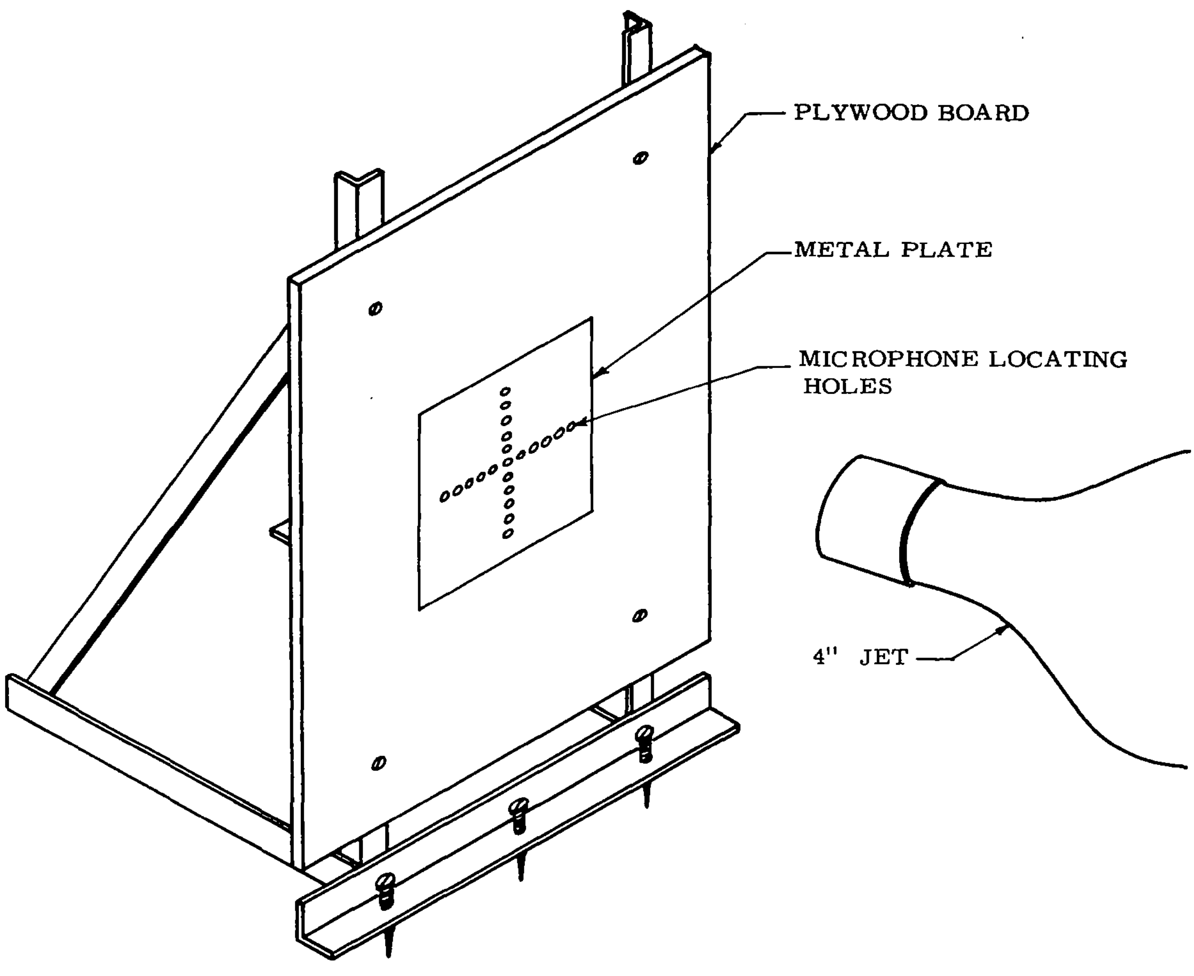

FIG. 1 SCHEMATIC DIAGRAM OF THE FLAT PLATE SET-UP

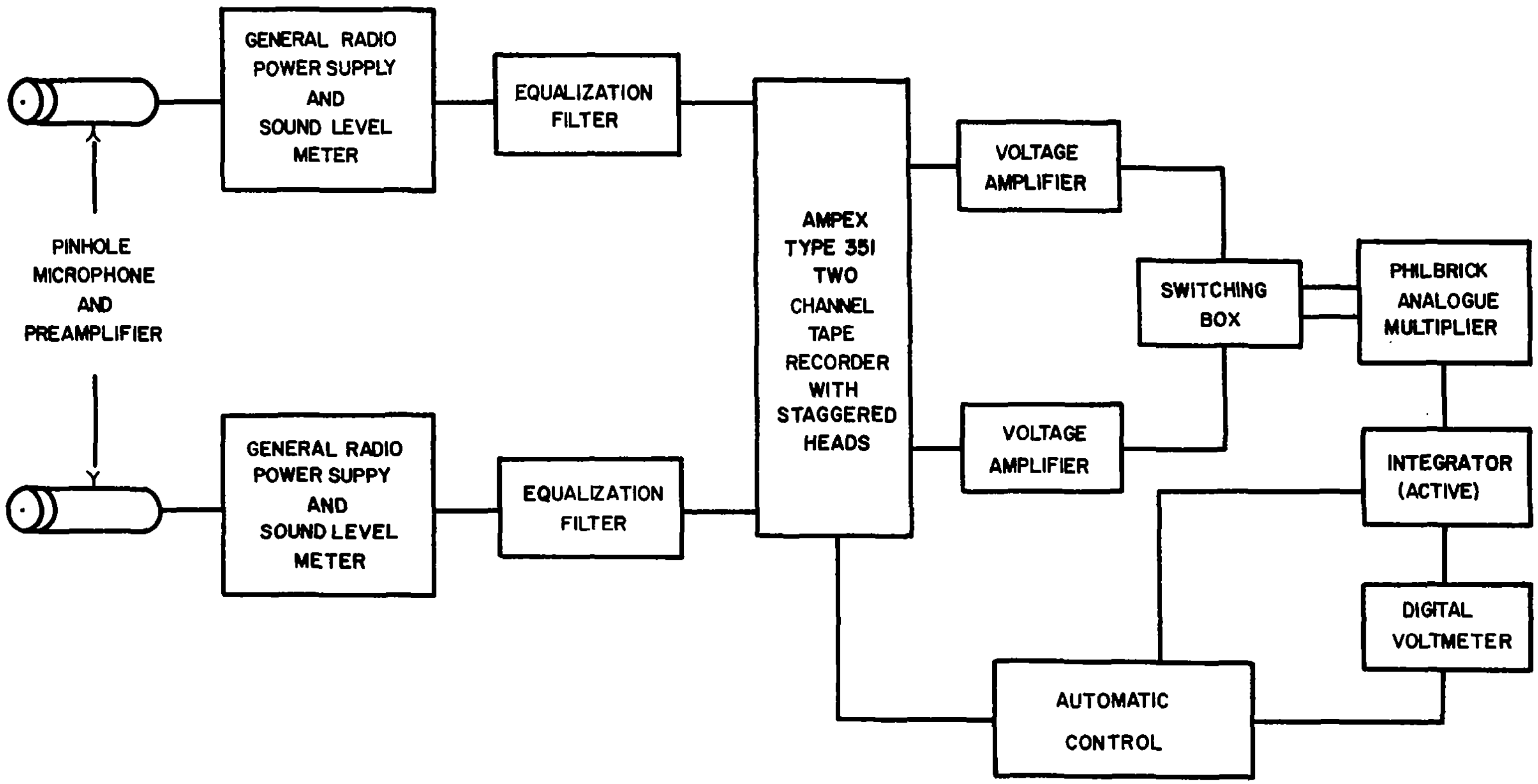

FIG. 2. BLOCK DIAGRAM OF ELECTRONIC CORRELATOR

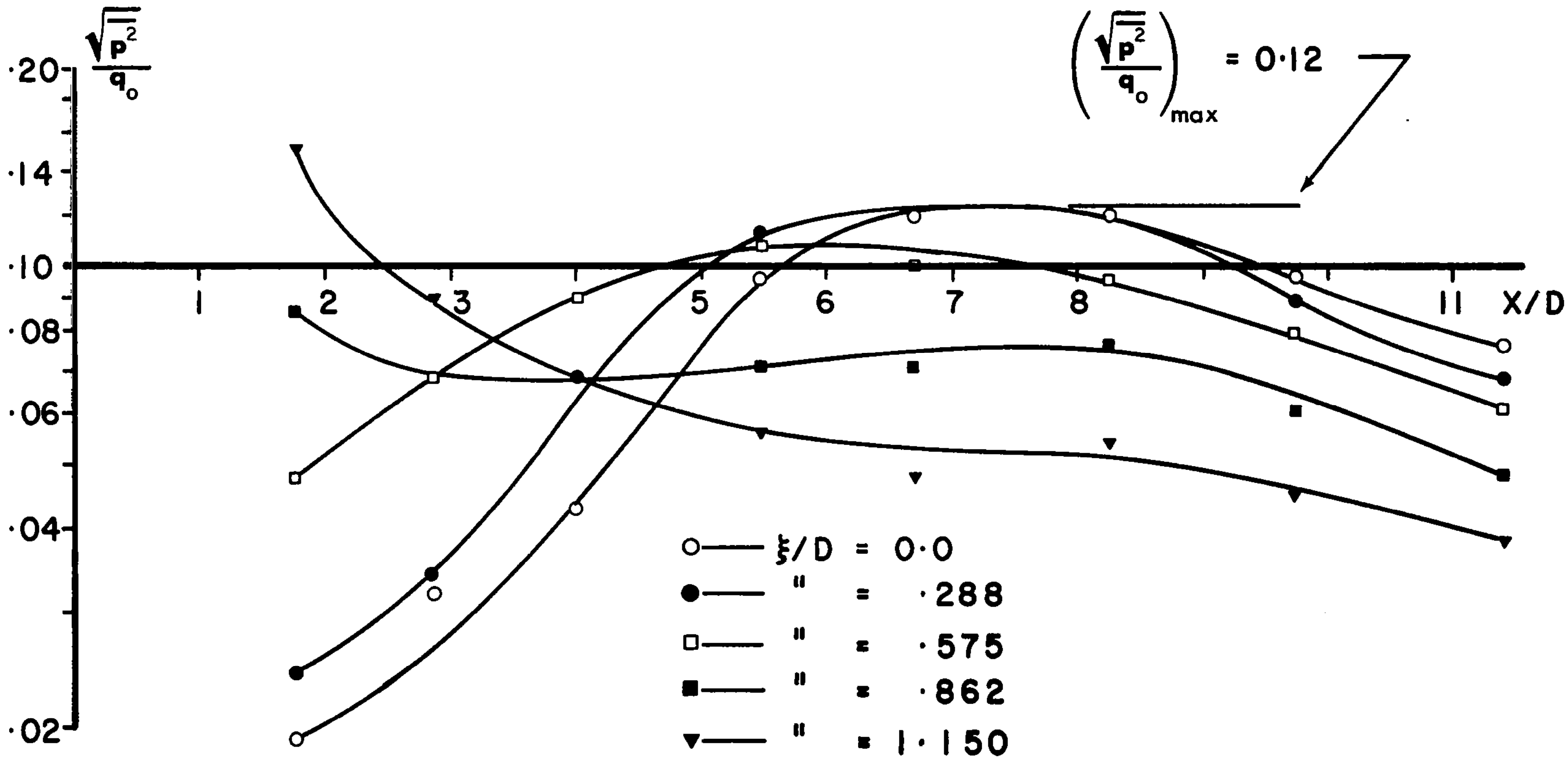

FIG. 3. SURFACE PRESSURE FLUCTUATION ON A FLAT PLATE DUE TO NORMAL JET IMPINGEMENT ($\Theta = 0^{\circ}$)

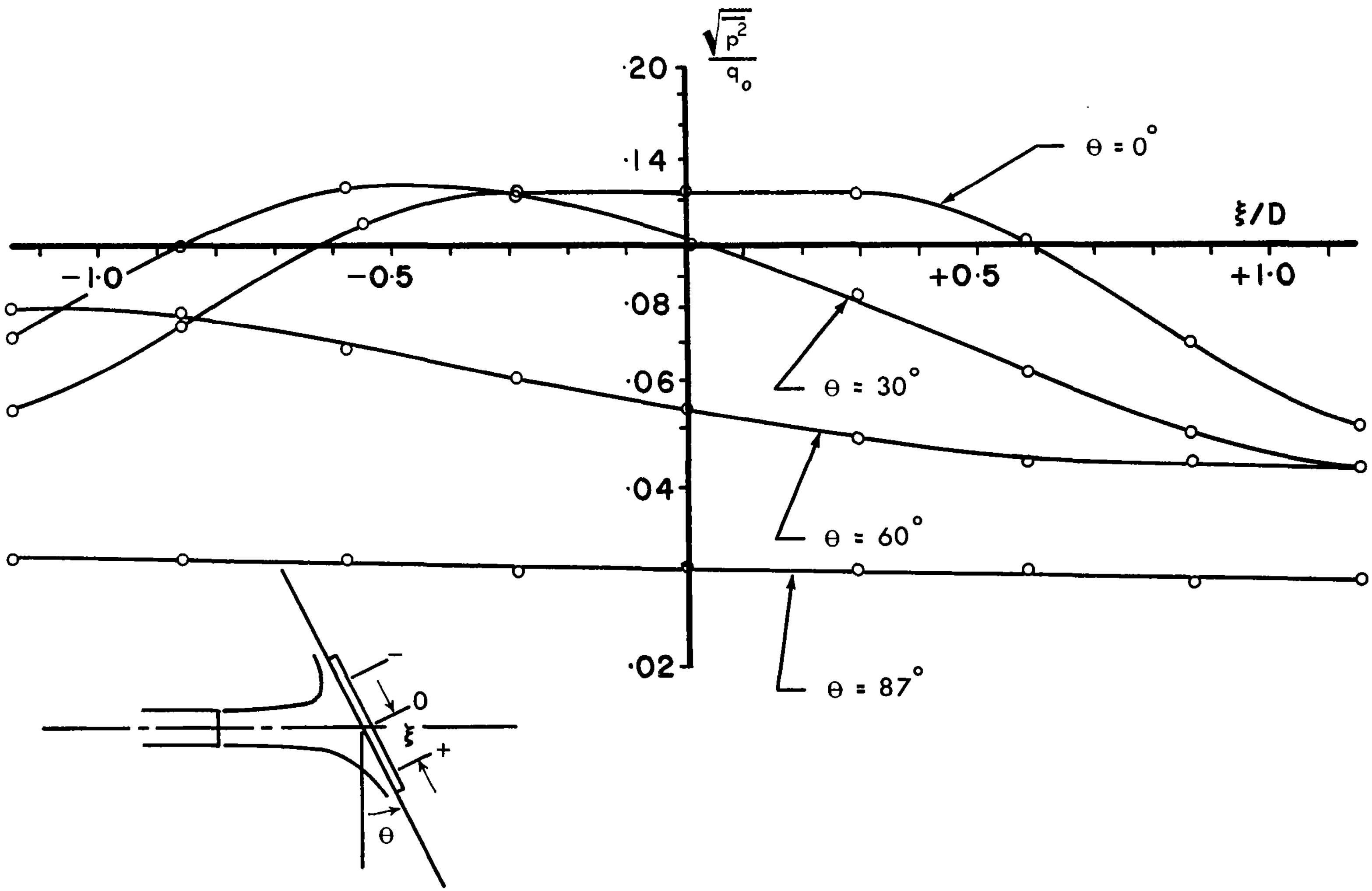

FIG. 4. SURFACE PRESSURE FLUCTUATION ON A FLAT PLATE DUE TO JET IMPINGEMENT AT X/D=7

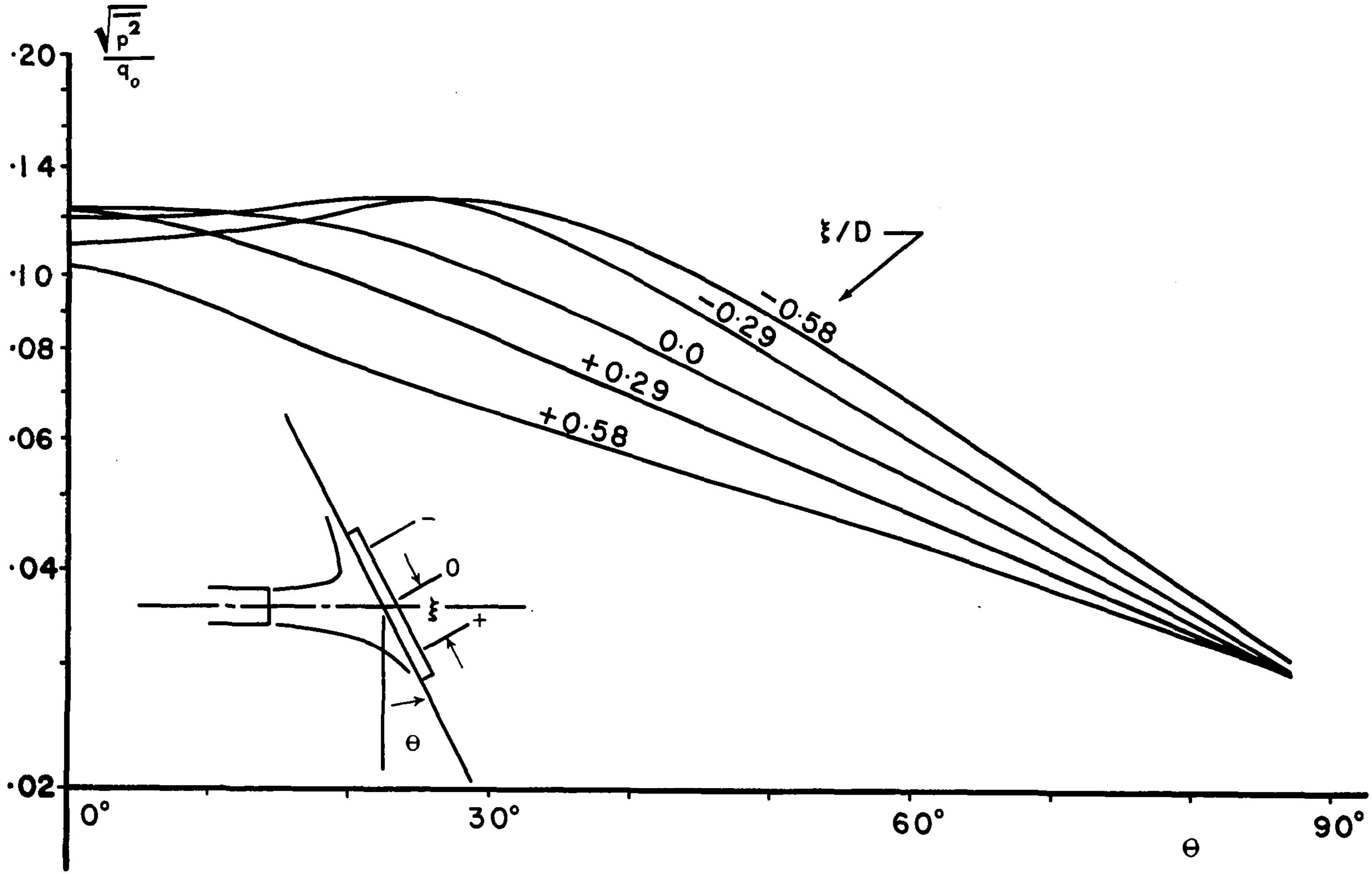

FIG. 5. VARIATION OF SURFACE PRESSURE FLUCTUATION WITH Θ FOR VARIOUS ξ/D (CROSS-PLOT OF FIG. 4)

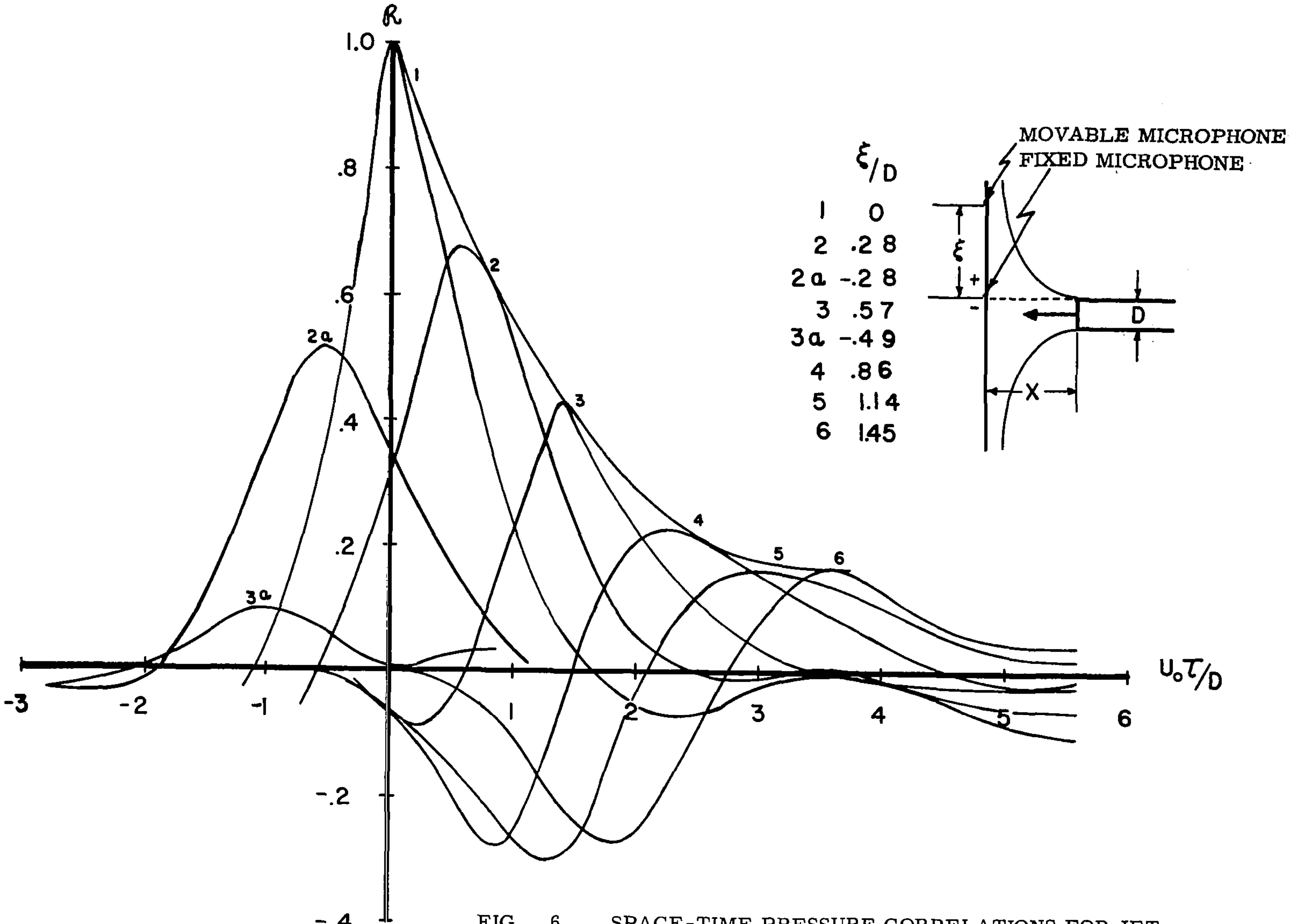

FIG. 6. SPACE-TIME PRESSURE CORRELATIONS FOR JET IMPINGEMENT (X/D=7 , Θ = 0°)

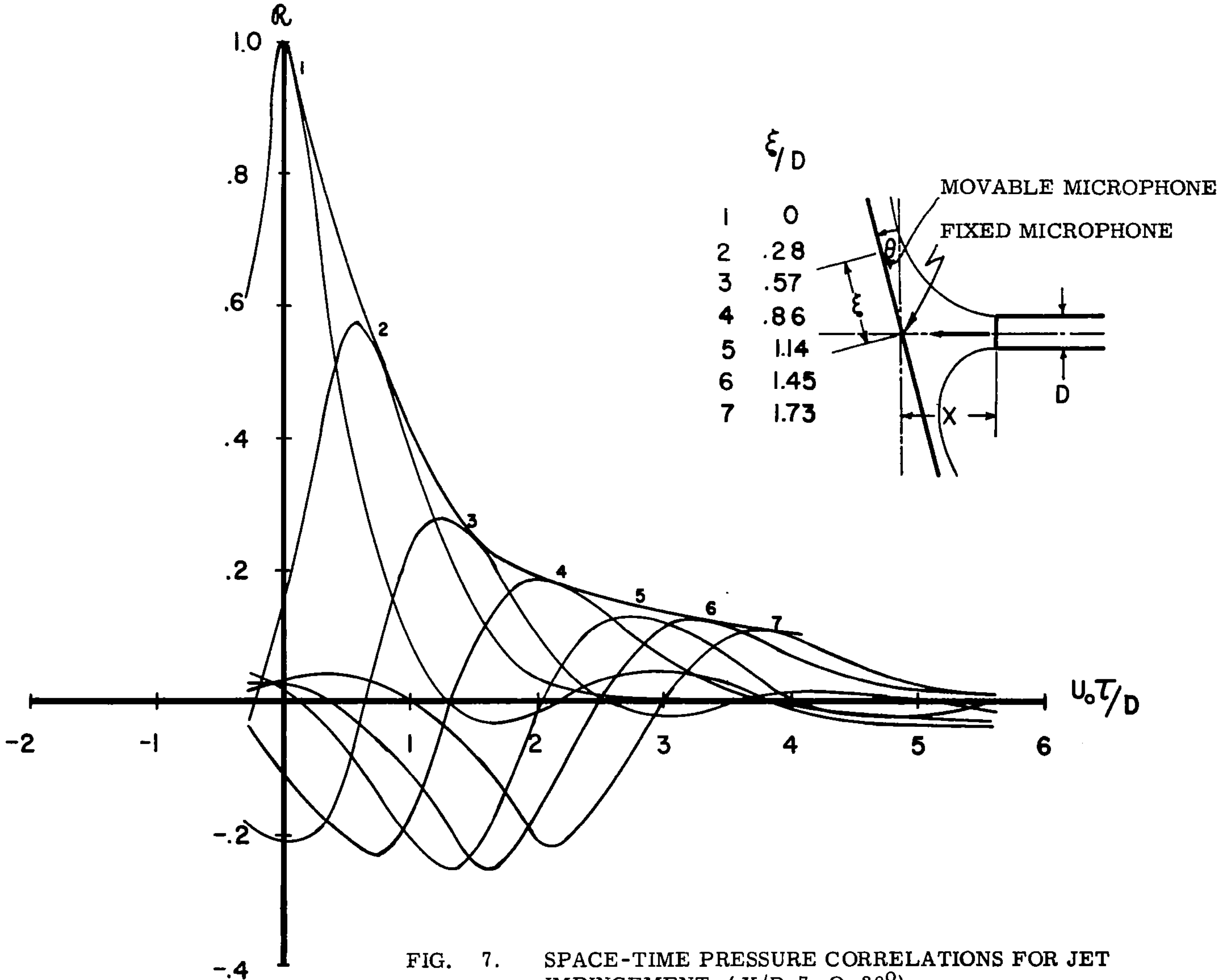

FIG. 7. SPACE-TIME PRESSURE CORRELATIONS FOR JET IMPINGEMENT (X/D=7 , Θ=30°)

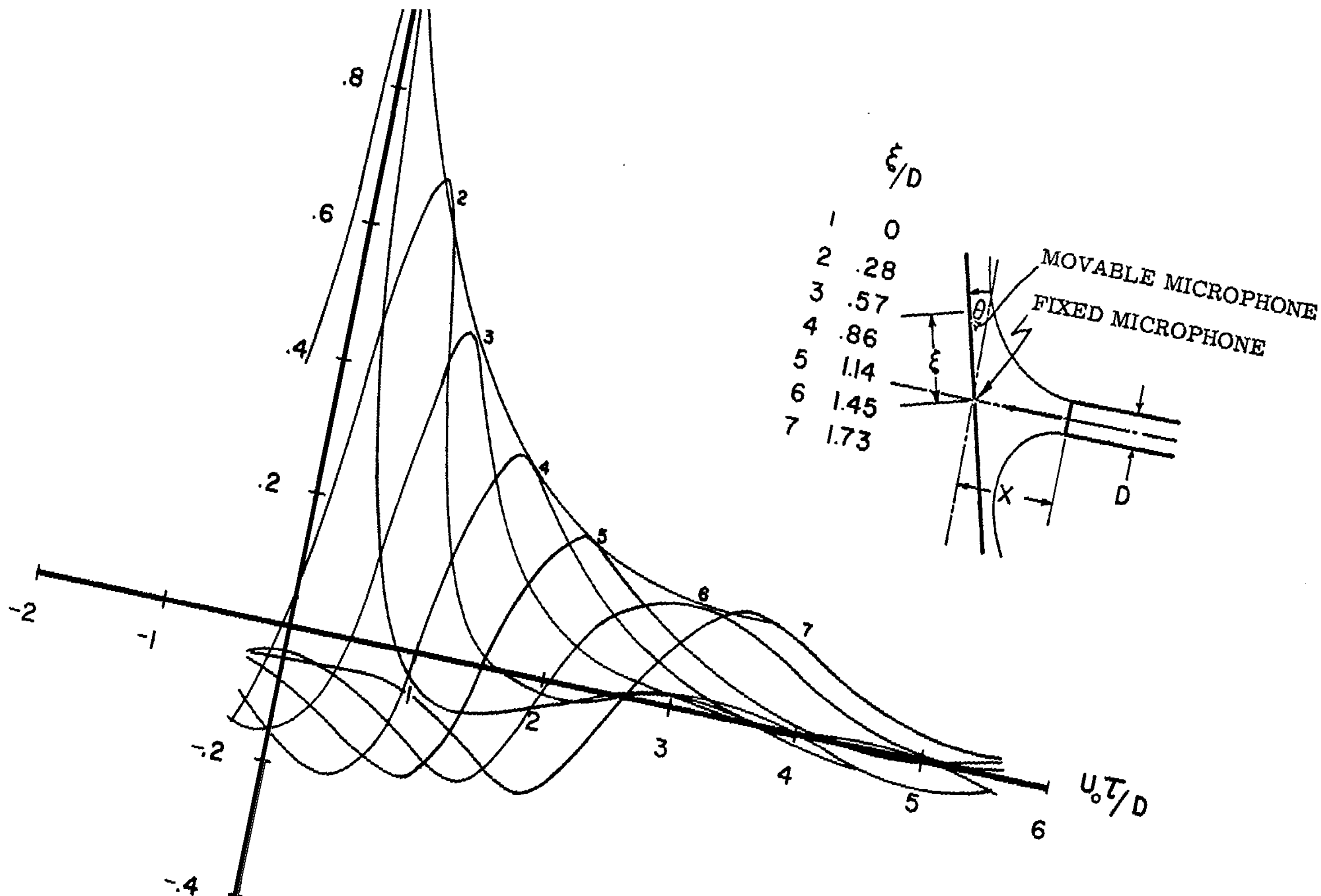

FIG. 8. SPACE-TIME PRESSURE CORRELATIONS FOR JET IMPINGEMENT (X/D=7, Θ= 60°)

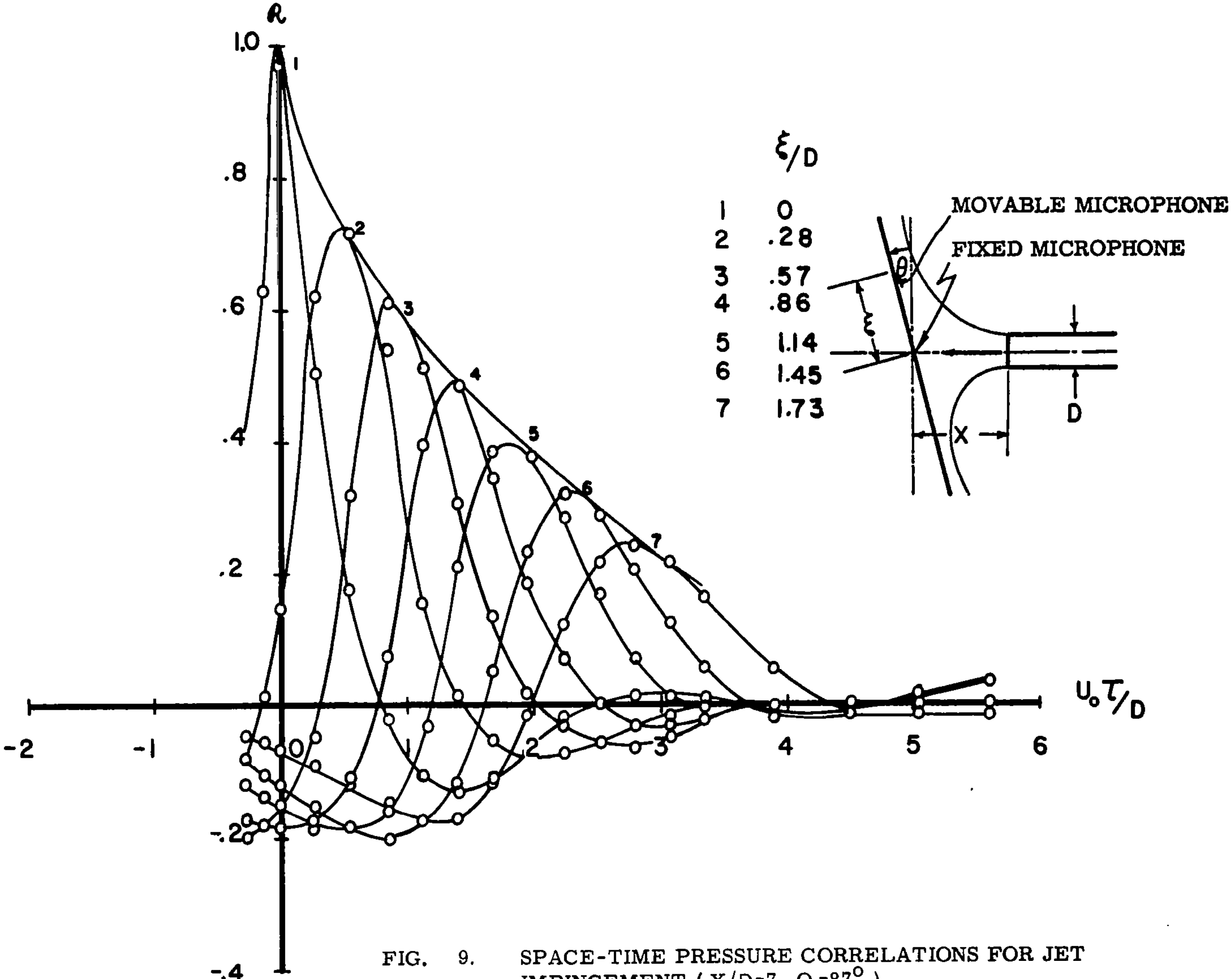

FIG. 9. SPACE-TIME PRESSURE CORRELATIONS FOR JET IMPINGEMENT ($X/D=7$, $\Theta=87^{\circ}$)

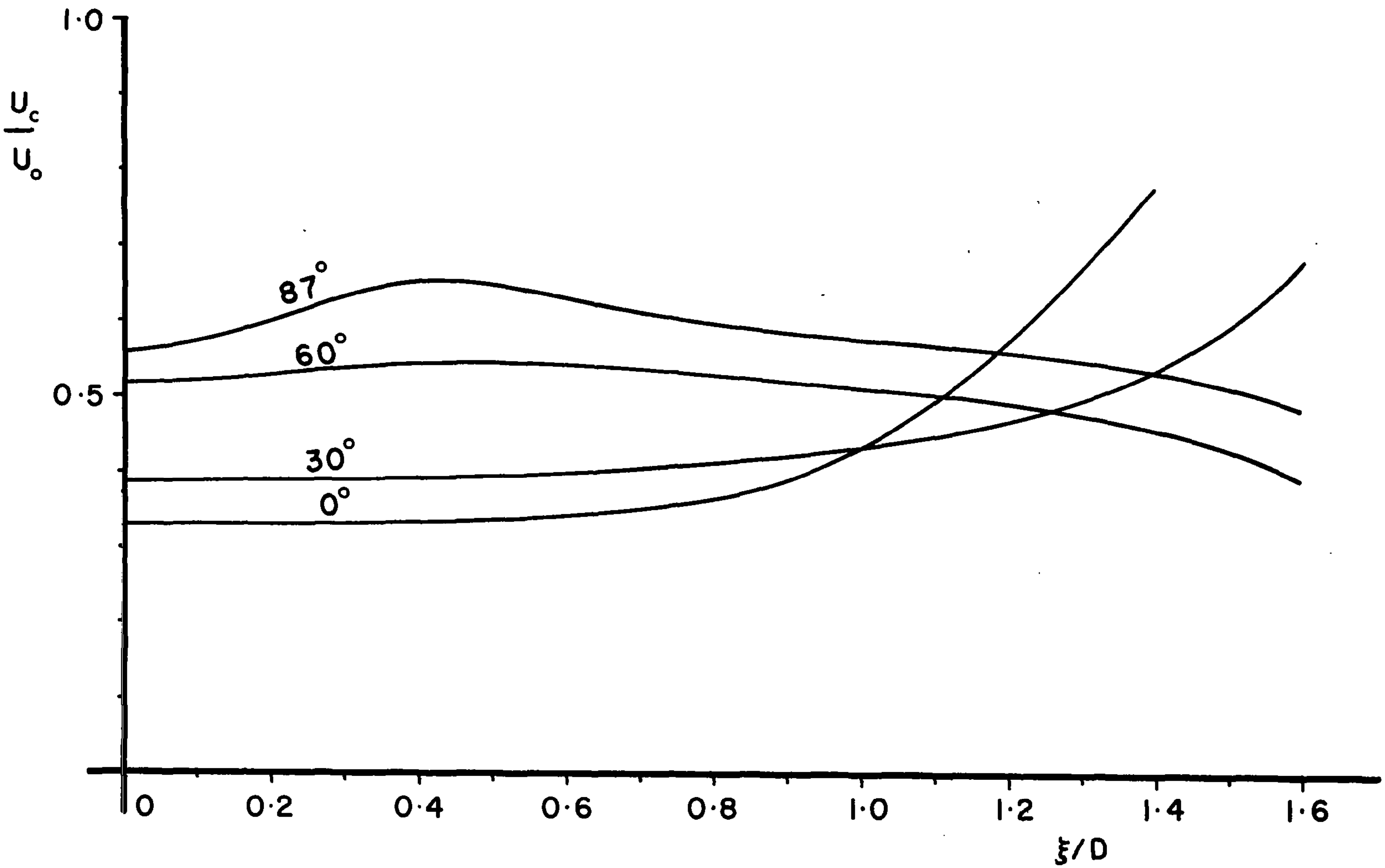

FIG. 10. VARIATION OF CONVECTION VELOCITY WITH ξ

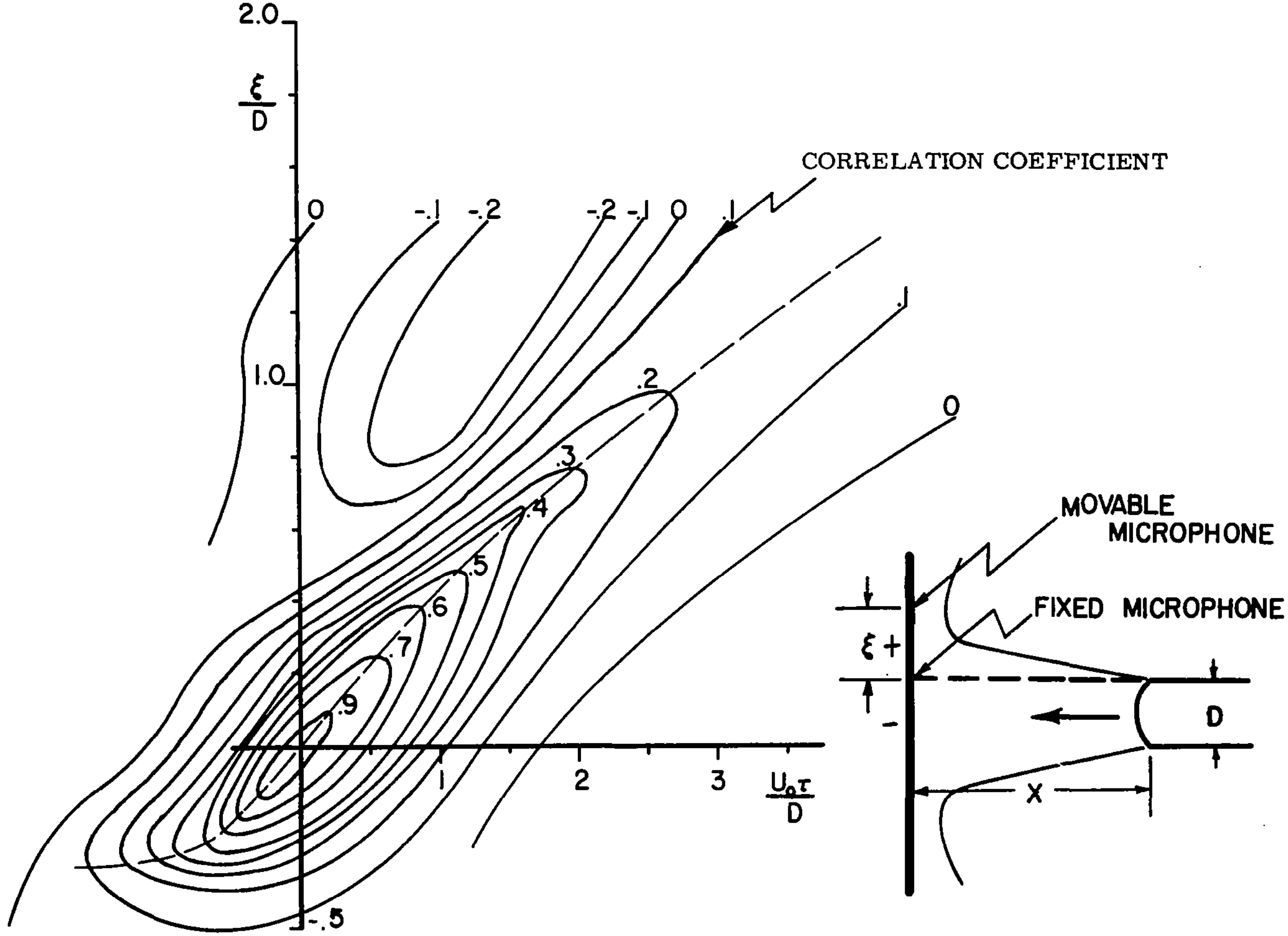

FIG. 11. ISOCORRELATION CURVES OF PRESSURE FLUCTUATION FOR JET IMPINGEMENT (X/D=7, $\Theta = 0^{\circ}$)

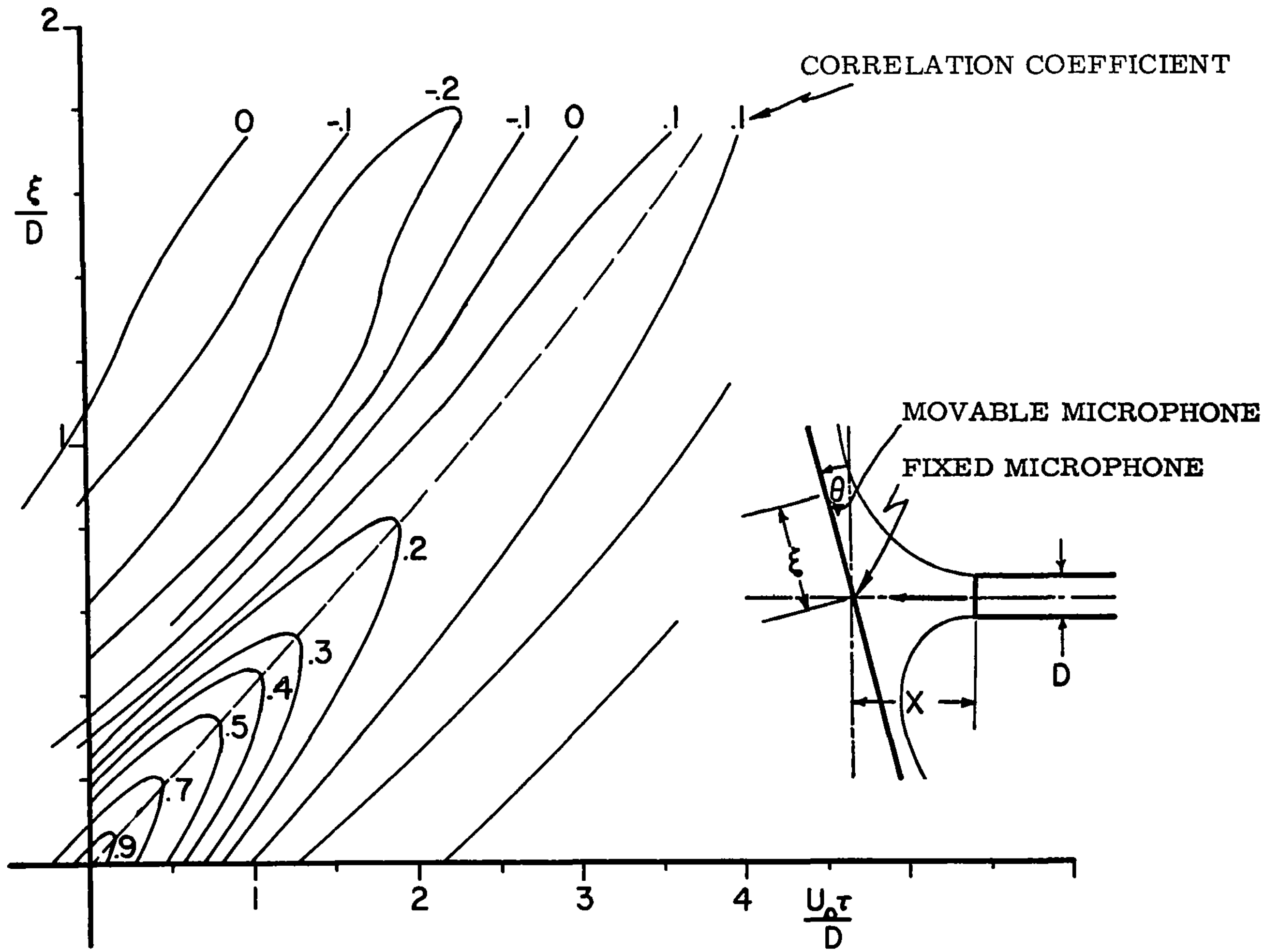

FIG. 12. ISOCORRELATION CURVES OF PRESSURE FLUCTUATION FOR JET IMPINGEMENT (X/D=7, Θ = 30°)

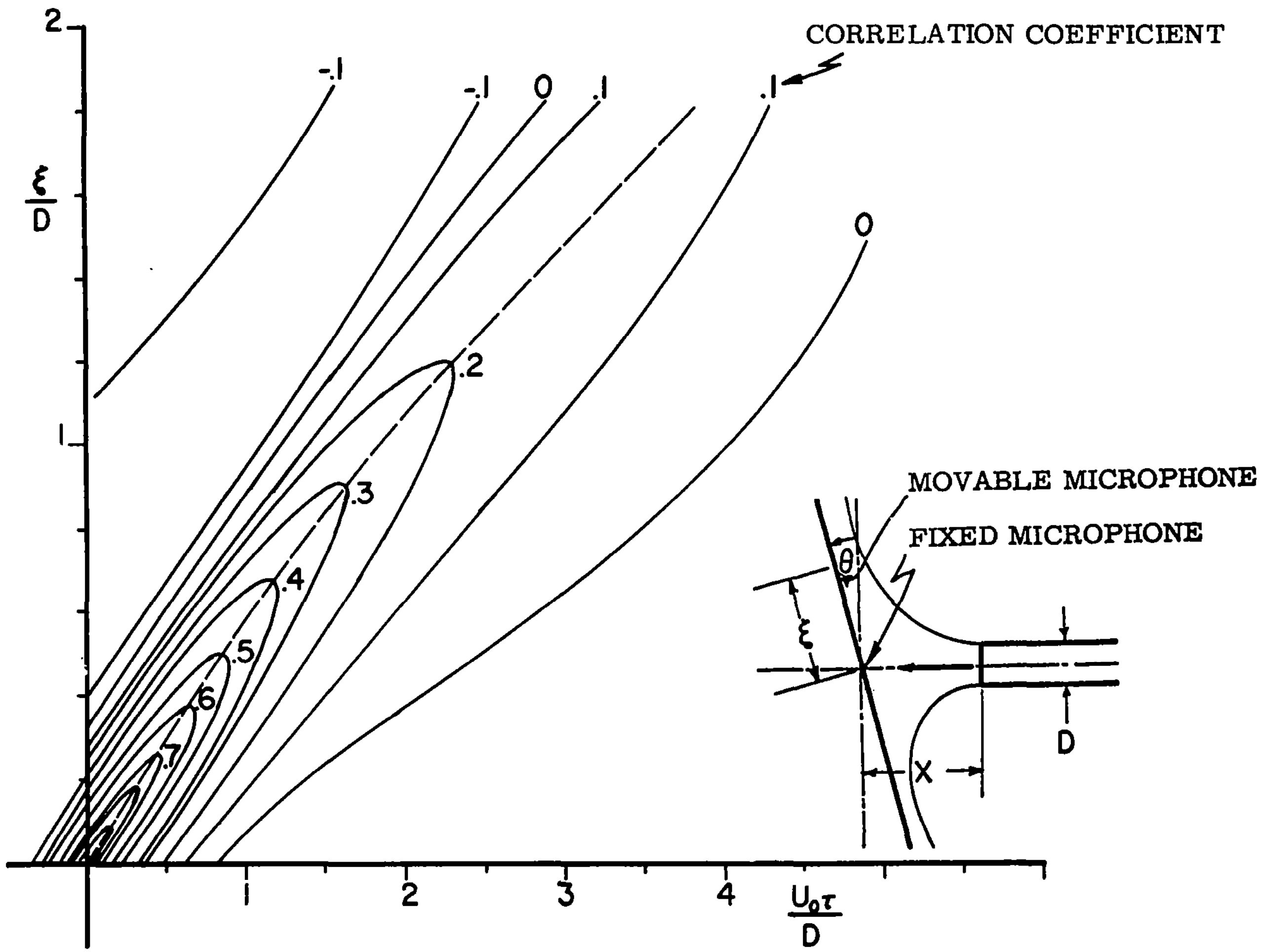

FIG. 13. ISOCORRELATION CURVES OF PRESSURE FLUCTUATION FOR JET IMPINGEMENT (X/D=7, Θ = 60°)

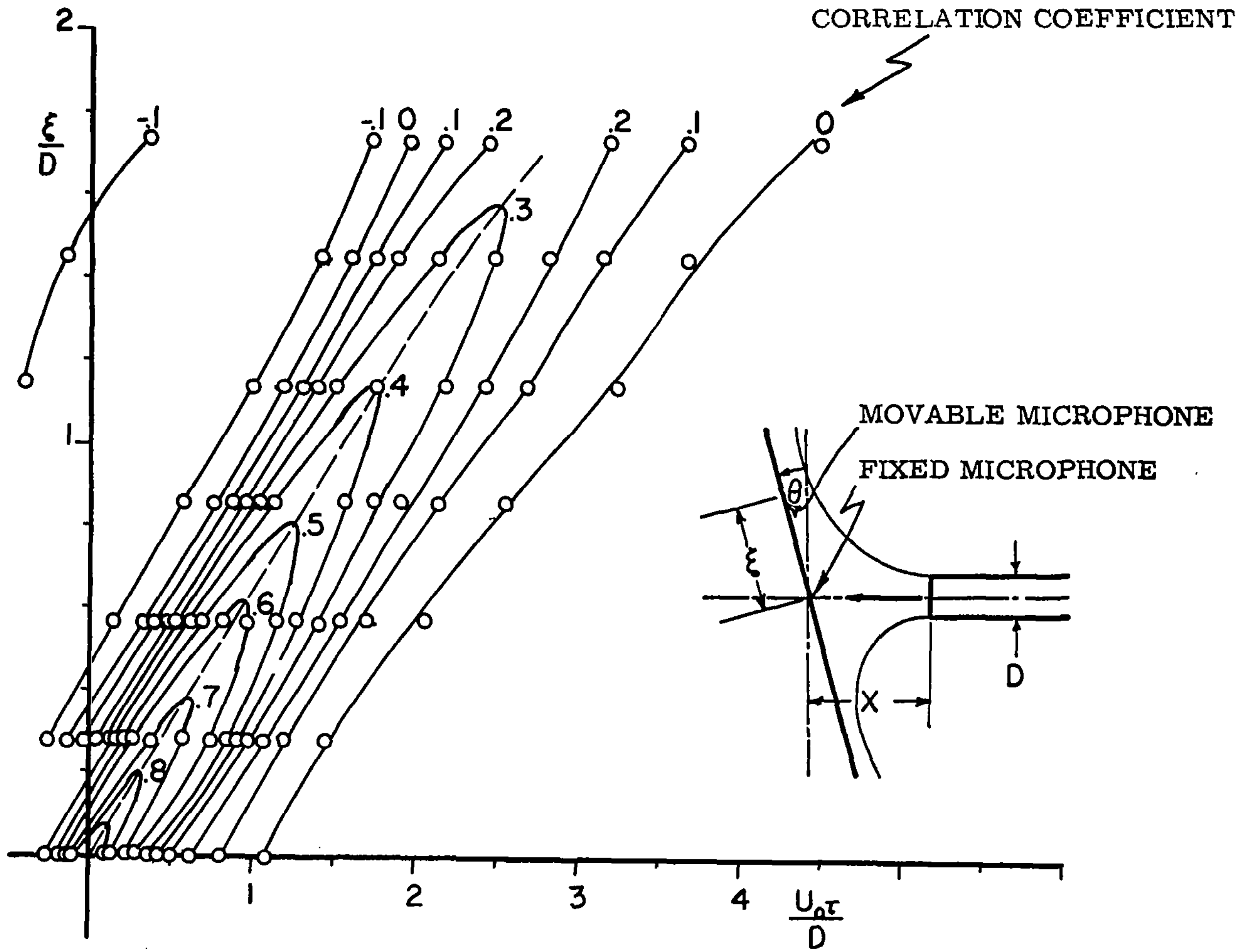

FIG. 14. ISOCORRELATION CURVES OF PRESSURE FLUCTUATION FOR JET IMPINFEMENT (X/D=7, Θ = 87°)

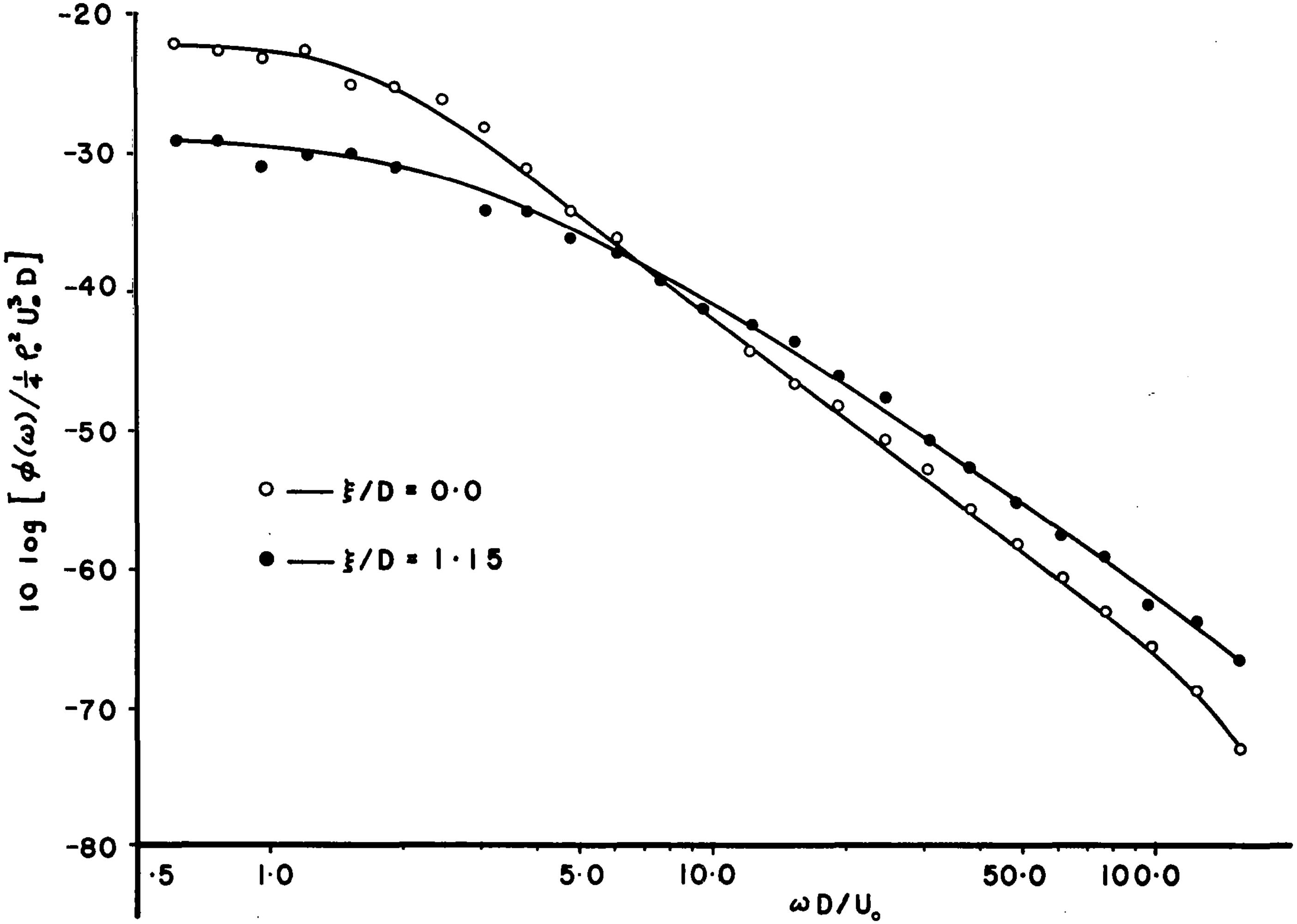

FIG. 15. SPECTRAL DENSITY OF PRESSURE FLUCTUATION AT X/D=7, ξ/D= 0 AND 1.15, FOR Θ = 0°

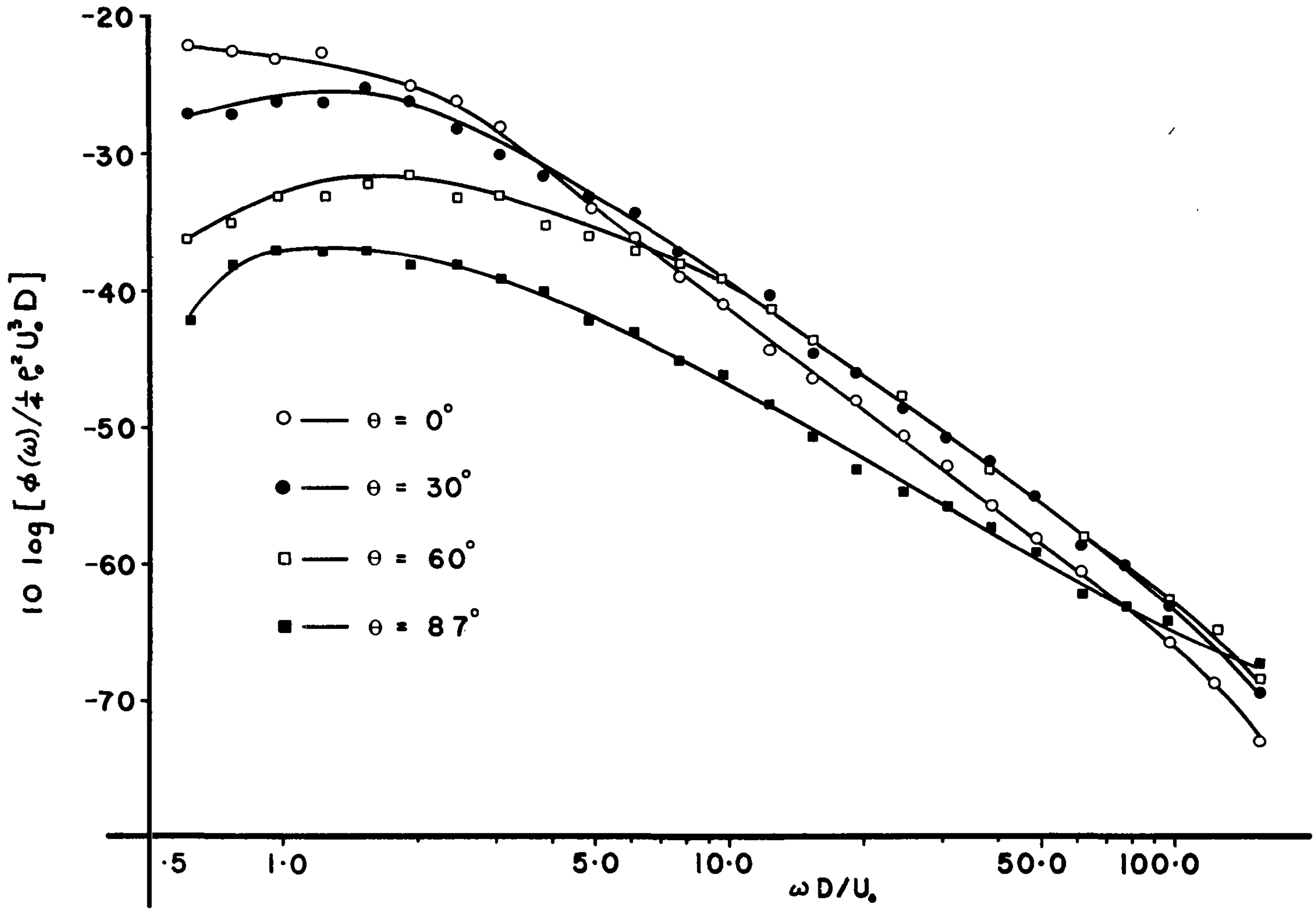

FIG. 16. SPECTRAL DENSITY OF PRESSURE FLUCTUATION AT X/D=7, ξ/D= 0, FOR VARIOUS Θ

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